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Form Approved
OMB No. 0704-0188

Pub[...] mai[...] sug[...] 222[...] 1 hour per response, including the time for reviewing instructions, searching existing data sources, gathering and [...]ation. Send comments regarding this burden estimate or any other aspect of this collection of information, including [...] Directorate for Information Operations and Reports, 1215 Jefferson Davis Highway, Suite 1204, Arlington, VA [...] Project (0704-0188), Washington DC 20503

1. AGENCY USE ONLY (Leave blank)	2. REPORT DATE	3. REPORT TYPE AND DATES COVERED
	August 1993	Professional Paper

4. TITLE AND SUBTITLE

SPORADIC-E OBSERVATIONS DURING LOVHF TRANSIONOSPHERIC DIRECTION FINDER MEASUREMENTS

5. FUNDING NUMBERS

PR: MP91
PE: 0601000N
WU: DN302027

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8. PERFORMING ORGANIZATION REPORT NUMBER

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)

Naval Security Group Commission
3801 Nebraska Avenue, N.W.
Washington, DC 20390

10. SPONSORING/MONITORING AGENCY REPORT NUMBER

11. SUPPLEMENTARY NOTES

12a. DISTRIBUTION/AVAILABILITY STATEMENT	12b. DISTRIBUTION CODE
Approved for public release; distribution is unlimited.	

13. ABSTRACT (Maximum 200 words)

A year long experimental program was conducted to measure refractive bending or how much the signal deviates from true line of sight, at low VHF (LoVHF) frequencies (29.5 MHz), and to determine whether this deviation or error could be predicted using large-scale ionospheric models such as the Ionospheric Conductivity and Electron Density (ICED) program. An experiment to directly measure the angle of arrival of a 29.5 MHz signal from an orbiting satellite was successfully completed. The satellite was in a circular orbit at an altitude of 1000 km. It was shown that refractive errors can be directly related to the electron density along the measurement slant range. The introduction of irregular patches of electron density occurring during sporadic-E events produced both horizontal and vertical gradients introducing large errors in both azimuth and elevation measurements. Nineteen test periods in May, June, July, and August 1989 were affected by mid-latitude sporadic-E with the daytime E-region critical frequencies (foEs) reaching 13 MHz in one case. This paper will present examples of these effects.

8 Pgs

Published in *IES 93: Proceedings for the International Ionospheric Effects Symposium* Fall 1993, pp. 3A1-1-1 to 3A1-1-7.

14. SUBJECT TERMS		15. NUMBER OF PAGES
Propagation Propagation Forecast Expert System	Prophet Solar Disturbances	16. PRICE CODE

17. SECURITY CLASSIFICATION OF REPORT	18. SECURITY CLASSIFICATION OF THIS PAGE	19. SECURITY CLASSIFICATION OF ABSTRACT	20. LIMITATION OF ABSTRACT
UNCLASSIFIED	UNCLASSIFIED	UNCLASSIFIED	SAME AS REPORT

21a. NAME OF RESPONSIBLE INDIVIDUAL	21b. TELEPHONE (Include Area Code)	21c. OFFICE SYMBOL
R. B. Rose	(619) 553-3069	Code 542

SPORADIC-E OBSERVATIONS DURING LOVHF TRANSIONOSPHERIC DIRECTION FINDER MEASUREMENTS

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ABSTRACT

A year long experimental program was conducted to measure refractive bending or how much the signal deviates from true line of sight, at low VHF (LoVHF) frequencies (29.5 MHz), and to determine whether this deviation or error could be predicted using large-scale ionospheric models such as the Ionospheric Conductivity and Electron Density (ICED) program. An experiment to directly measure the angle of arrival of a 29.5 MHz signal from an orbiting satellite was successfully completed. The satellite was in a circular orbit at an altitude of 1000 km. It was shown that refractive errors can be directly related to the electron density along the measurement slant range. The introduction of irregular patches of electron density occurring during sporadic-E events produced both horizontal and vertical gradients introducing large errors in both azimuth and elevation measurements. Nineteen test periods in May, June, July and August 1989 were affected by mid-latitude sporadic-E with the daytime E-region critical frequencies (foEs) reaching 13 MHz in one case. This paper will present examples of these effects.

INTRODUCTION

NCCOSC RDT&E Division (formerly the Naval Ocean Systems Center) conducted a year long experimental program in 1989 to measure and predict measurement errors caused by ionospheric refractive bending at low VHF (LoVHF) frequencies (29.5 MHz). The approach was to measure how much the path of a satellite signal deviated from true line of sight after it had passed through the ionosphere and then to determine whether this deviation or error could be predicted using large-scale ionospheric models such as the Ionospheric Conductivity and Electron Density (ICED) computer program. An experiment was successfully completed which directly measured the angle of arrival of a 29.5 MHz satellite signal. The results show that refractive errors of a transionospheric signal are directly related to the electron density measured along the signal path. During mid-latitude sporadic-E events, patches of irregular electron density occurred. They exhibited both horizontal and vertical density gradients which caused large errors in both azimuth and elevation measurements, respectively. Sporadic-E was frequently observed, with daytime critical frequencies (foEs), which normally range between 2 and 5 MHz, rising to as high as 13 MHz.

EXPERIMENTAL METHOD

Conceptually, the experiment was simple. Radio signals from a satellite were observed by a ground station and analyzed, treating them as point sources. The "apparent" direction of the satellite from the ground station was measured and compared with the "real" direction. The difference, expressed in angular error in degrees, is the refractive bending error caused by the ionosphere between the satellite and the ground station.

The signal source for this experiment was a 29.5 MHz beacon aboard a low orbiting, navigational satellite (NAVSAT). The satellite contained a LoVHF beacon which produced Morse code signals at 29.5 MHz. This was fortunate for our transionospheric measurement purposes because the NAVSAT's orbit was circular, accurately maintained at a 1000 kilometer altitude, which encompasses 98 percent of the ionosphere. Data was collected every 15 seconds as long as the 29.5 MHz beacon signal strength was sufficient for gathering data. The satellite's orbital inclination of 83 degrees provided two or three useful passes a day, each normally lasting 12-13 minutes from horizon to horizon.

The real direction of the satellite was derived from predicted ephemeris data which specified the orbital location of the satellite in space and time. The apparent direction of the satellite-borne beacons was measured with a Single Site Locating (SSL) Testbed at Southwest Research Institute (SwRI) in San Antonio, Texas. These measurements required a direction finder with fast processing time which could make high time-resolution measurements of angle of arrival (AOA) in azimuth and elevation. At the time the experiment was conducted, the SwRI SSL system was the only one in existence with this capability. It can perform successive angle of arrival measurements at 3.5 millisecond intervals.

The SwRI SSL system, described in some detail elsewhere (Rose 1992), is a 7-element interferometer which uses an "L" shaped antenna array. Each set of 7 AOA phase measurements, one from each of the 7 array elements, constitutes one 3.5 millisecond "frame" of data. Each frame was time tagged and stored on magnetic media. Next, each frame underwent phase linearity testing. This test determined whether the array had observed a plane-wave and had made an AOA observation based on just one signal. The frames that passed this test, typically 100-500 of the 1152 collected in each window, were stored in a file for further processing. A final step converted this data to spreadsheet format for analysis.

The 3.5 millisecond sampling rate produces large amounts of data very quickly. Because of this, the length of each data collection period was limited to a four-second window, or 1152 3.5-millisecond frames every 15 seconds. This sampling rate is fast enough to effectively minimize errors due to satellite motion. The satellite moved approximately 26 meters between frames, or about 30 km during each 4 second window.

In addition to the satellite beacon measurements, ionospheric soundings were made before and after each satellite pass during the entire experimental period. The sounder makes vertical incidence measurements over a range of frequencies and generates an ionogram. This was done to determine ionospheric conditions, measure the F-region critical frequency, foF2, and calculate the peak electron density. Peak electron density (Ne) is directly related to foF2 by the formula:

$$\text{Ne (electrons/cm}^3\text{)} = 1.24\text{x}10\text{E}4 \text{ x foF2 (MHz)} \quad (1)$$

The refractive bending data was then plotted as a function of peak electron density for later comparison with ionospheric models.

DISCUSSION OF THE DATA

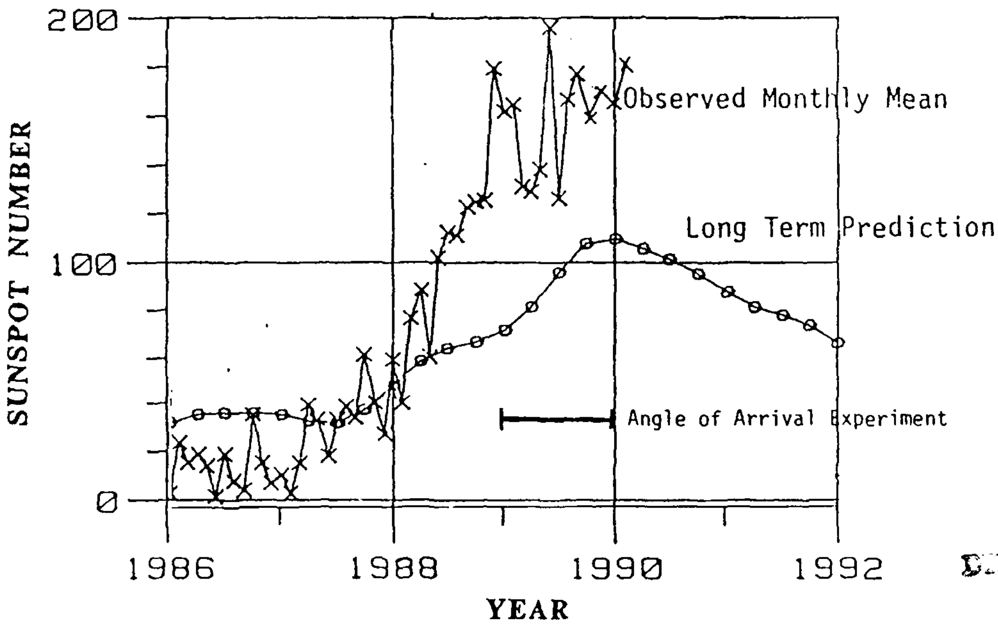
The experimental program was conducted between October 1988 and December 1989. Over this period, 210 passes provided information that were suitable for analysis. These included:

28 Cases - Setup/Calibration - (October - December 1988)
40 Cases - Winter (January - March 1989)
40 Cases - Spring (April - June 1989)
50 Cases - Summer (July - September 1989)
52 Cases - Fall (October - December 1989)

This experiment performed above expectations throughout the year with respect to the amount, uniqueness, and value of the data collected. There was no day or time in which data could not be acquired. And, as is seen in figure 1, this experiment was conducted at the peak of solar cycle 22 during the period in which solar activity reached all-time record levels of activity.

Figure 1

SOLAR CYCLE 22: PREDICTED VS. OBSERVED
(Extrapolation Based on 1840-1983 Data)



The times of day during which signals could be received changed daily because of the satellite's orbit. This allowed a measurement schedule that could probe the ionosphere at different times of day and night. The periods at pre-sunrise (electron density minimum) and shortly after midday (electron density maximum) were always the most interesting. For example, at pre-sunrise in the winter the electron density becomes very low. This allows the scientist to determine the baseline accuracy of the interferometer without interference from the ionosphere.

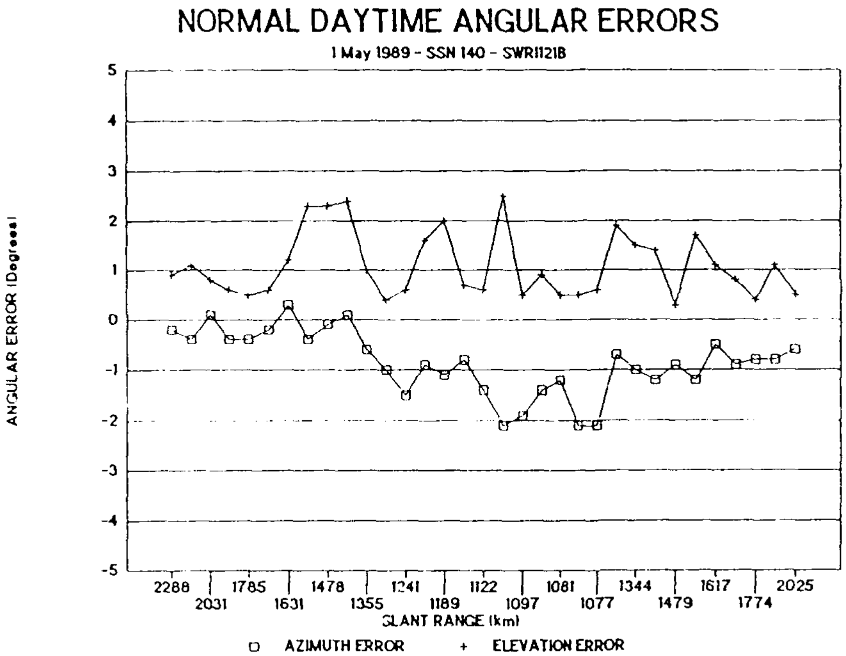
Data collection became straightforward once elevation angle boundaries were established. Most of the data were collected between elevation angles of 20 and 82 degrees. Below 20 degrees, the slant ranges exceed 2000 km, the signal-to-noise ratio is very poor and the likelihood of an undistorted plane wave signal is very low. Above 82 degrees (directly overhead) the arctangent calculation used in determining the azimuth angle of arrival breaks down and answers are unreliable.

The predicted ephemeris data were checked on each pass by carefully observing the times of acquisition of signal (AOS) and loss of signal (LOS). These normally occur as the satellite crosses over the horizon into or out of line of sight of the receiving station. Any error in the predicted ephemeris data showed up as a bias in the angular error data and was easily spotted. The most reliable test on ephemeris accuracy was AOS on a north to south pass, for which predicted and observed times never differed by more than several seconds. In contrast, prediction of LOS to the south was completely unreliable. Differences between predicted and observed values ranged from tens of seconds to minutes.

Several trends appeared early in the tests and it soon became easy for the analyst to discern whether the pass was north to south or vice versa. The large patches of ionospheric irregularities that characterize latitudes below 30 degrees north latitude were evident. The ionosphere to the north of the receiver site was less dense than to the south. Changes in signals from the north were orderly and at expected levels. Signals from the south were always variable and unpredictable, with greater errors at long slant ranges.

The ionospheric electron density, and the resulting refractive angular error, does not change in a smooth manner and is not uniform in "texture" even during normal, undisturbed times when its values are low. Figure 2 shows the variations in azimuth and elevation angular errors which were typically observed as the satellite passed overhead. These observations are for midday at solar maximum when electron densities are at their peak. With few exceptions, figure 2 is representative of refractive error caused by the ionospheric F-region without any E-region intervention. Although there are one-degree variations, the errors tend to change in a relatively orderly manner.

Figure 2



SPORADIC-E AT LOVHF FREQUENCIES

During normal conditions, the effects of the E-region can generally be discounted as a source of transionospheric refractive error. However, the E-region has a nomadic cousin, called **sporadic-E (Es)**, which abruptly occurs and disappears at heights between 95 and 115 kilometers. A sporadic-E event is defined to be occurring when the E-region critical frequency rises above 5 MHz. Signals that would normally penetrate the ionosphere are then reflected and terrestrial signals above 30 MHz will often be heard over long distances. Traditionally, the presence of sporadic-E goes unnoticed by the majority of the HF users except those using frequencies above 25 MHz. During the experimental period the sporadic-E critical frequency varied from 5 MHz up to 13 MHz, which is exceptionally high. When it reaches this value, the maximum usable frequency (MUF) is near 65 MHz.

A typical sporadic-E layer is thin, normally not exceeding 5 kilometers, and may extend over an area several hundred kilometers in length. It resembles a "patchwork quilt", containing intensely ionized patches with scale sizes on the order of a few tens of kilometers. These patches have exceptionally high ion densities or exceptionally large ion density gradients, or both. Mid-latitude sporadic-E occurrence peaks in the northern hemisphere in May, June and July, with minor peaks December and January [McNamara 1991]. However it can appear at any time with lesser durations and intensities. The occurrence of sporadic-E is not dependent on the solar cycle and its association with weather is uncertain. Sporadic-E is more frequent during local morning and prior to sunset [Goodman 1992]. Its probability of occurrence is negatively correlated to magnetic index: when the Kp or A-index rises, the probability of Es decreases [Cohen and Jacobs, 1973].

The transionospheric experiment's use of an orbiting signal source provided a unique opportunity to "map" the intensity of sporadic-E clouds during June 1989. The sporadic-E data was assembled, analyzed, and reviewed separately from the rest of the data to learn whether any of the characteristics of mid-latitude Es could be characterized and modeled. The following sections present a few examples of our observations. No clear pattern emerged.

Figure 3 shows a typical daytime sounder ionogram taken at midday in San Antonio. The E-region critical frequency is at a normal daytime value of 4 MHz and no sporadic-E is evident.

Figure 3

VERTICAL SOUNDER IONOGRAM

Typical Day Without Sporadic-E

16 May 1989

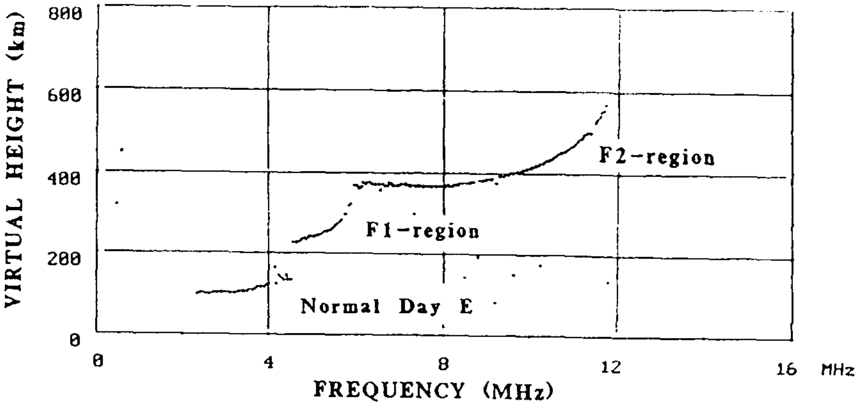


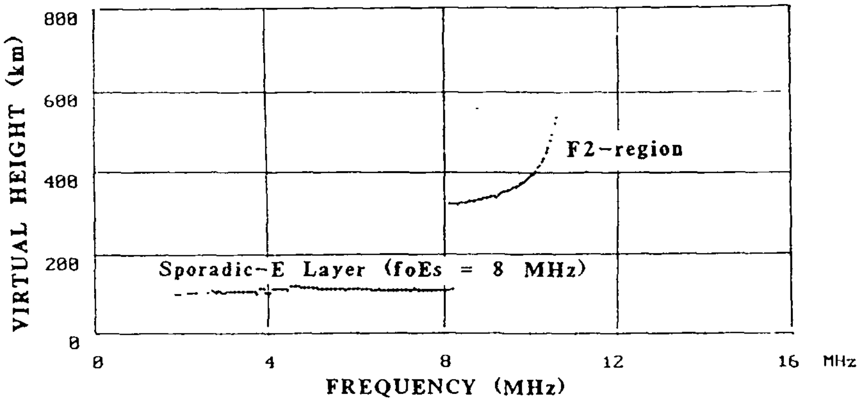
Figure 4 shows an example of a sporadic-E event measured by the sounder. The sporadic-E layer so is dense that the F-region cannot be seen. This is called blanketing. In this example the E-region critical frequency is 8 MHz, indicating that terrestrial skywave signals of up to 40 MHz can be sustained in this geographical region.

Figure 4

VERTICAL SOUNDER IONOGRAM

Daytime Blanketing Sporadic-E

5 July 1989



As mentioned earlier, an objective of this project was to define general features that could be expected once a local Es event was sensed. The following examples and accompanying figures 5, 6, 7, and 8 illustrate why this is difficult. The examples show the variation in azimuth and elevation error as a function of slant range from the interferometer. In cases where the satellite passed directly overhead, the minimum slant range is 1000 km.

Figure 5 shows data from a pass at 0900 local time on 30 June 1989. The satellite passed from north to south (plotted from left to right in the figure), almost overhead. The E-region critical frequency was measured at 10 MHz. Major perturbations in elevation angles are seen at extreme slant ranges around 2300 km, which indicate extreme vertical gradients. The temporal duration, and therefore spacial extent, of these large errors indicates a large patch of ionization. At intermediate ranges, between 2133 km and 1331 km, both elevation and azimuth angular errors are very small. Then, between ranges of 1331 km and 1262 km, the azimuth error oscillates as the satellite rises above 45 degrees to the north and proceeds past 45 degrees elevation to the south. The oscillatory nature of the azimuthal errors indicates large patches of ionization that are elongated in the direction of the satellite's

path. The lack of oscillatory features in the elevation data indicates the cloud has a relatively uniform vertical electron distribution. This sporadic-E cloud extends lengthwise along the satellite path over 600 km on either side of the measurement site. At a slant range of 1262 km to the south, the edge of the cloud is passed as evidenced by an abrupt return to minimal angular errors. The errors increase once again at the longer slant ranges just before LOS.

Figure 5

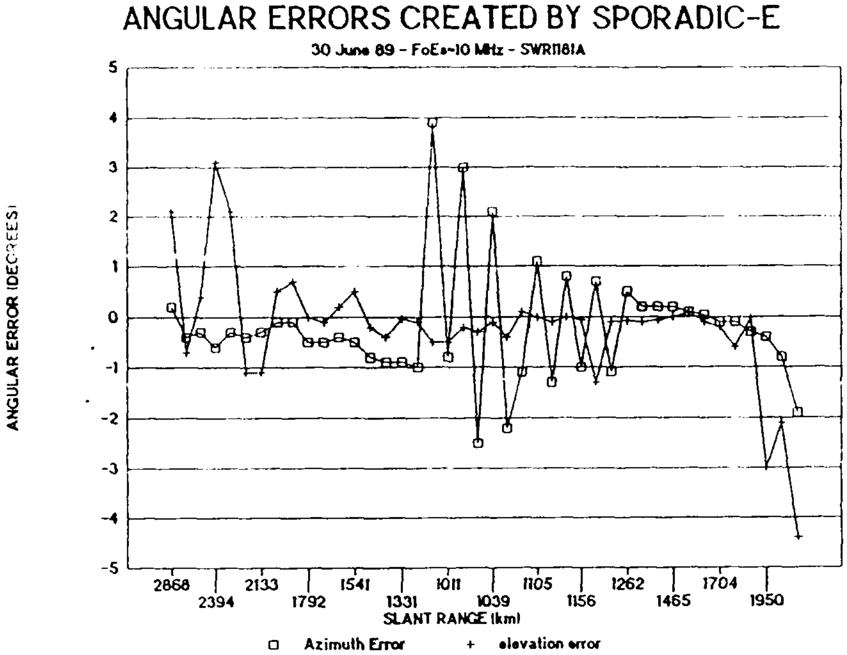


Figure 6 shows another example of a sporadic-E event with exceptionally high electron densities, one which occurred on 21 June 1989. The satellite pass was from south to north, virtually straight overhead. (Although the direction of this pass is opposite that in the previous example, it is still plotted from left to right in the figure.) The E-region critical frequency rose to 13 MHz, corresponding to a circuit MUF near 65 MHz. Once again, as in figure 5, the cloud extends for hundreds of kilometers over the observation site. In this case, however, the highly ionized irregularities are oriented at an oblique angle to the transit path rather than along it, and both the azimuth and elevation measurements show oscillatory characteristics. Also the bounds of the cloud are easily seen at slant ranges of 1189 km to the south and 1246 km to the north.

Figure 6

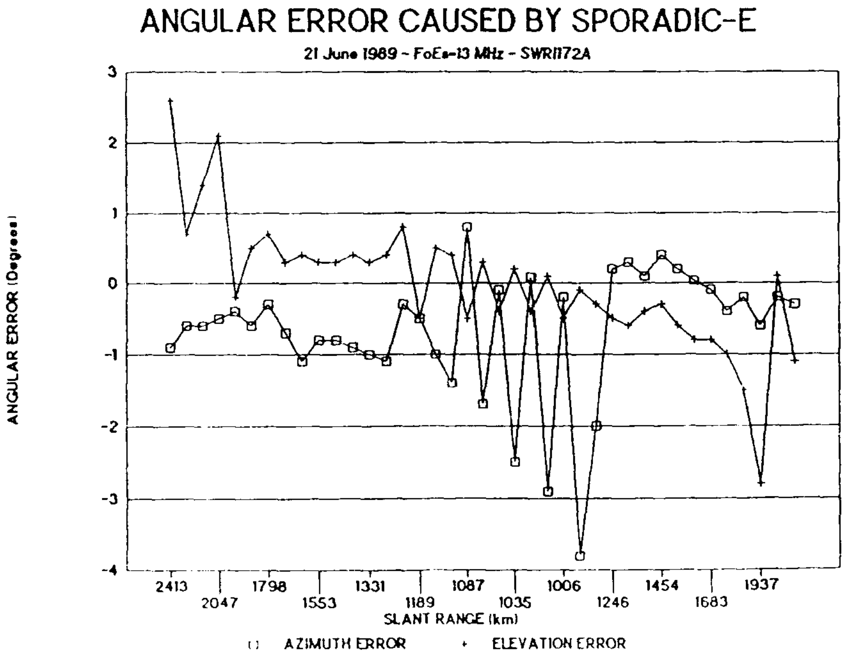


Figure 7 shows a similar sporadic-E event which occurred on 15 June 1989. The pass was from north to south, to the west of the interferometer. As in the previous example, the E-region critical frequency was 13 MHz. The vertical sounder showed that the E-region was very intense, blanketing any returns from the F-region. In this case the cloud has a more uniform density, as evidenced by the lack of extreme error oscillations in the azimuth and elevation measurements. The edge of the cloud is seen at a slant range of 1313 km to the south.

Figure 7

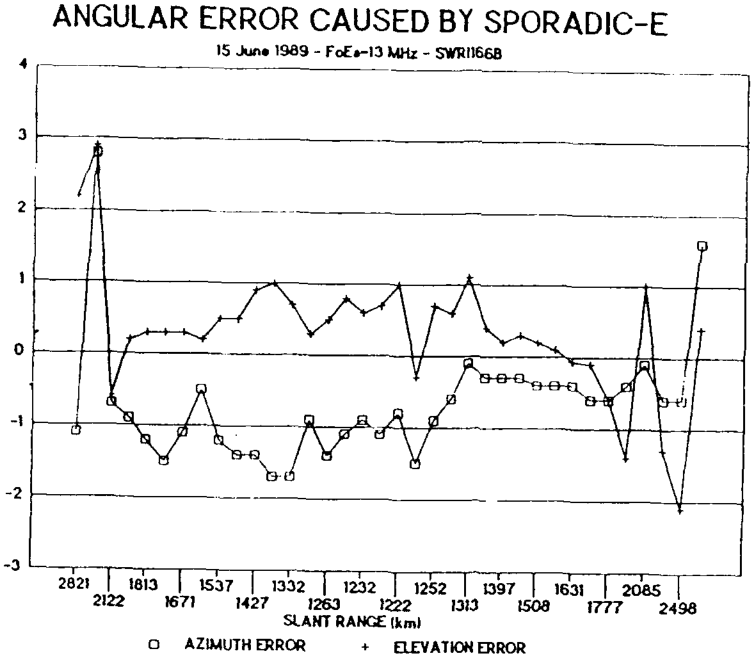
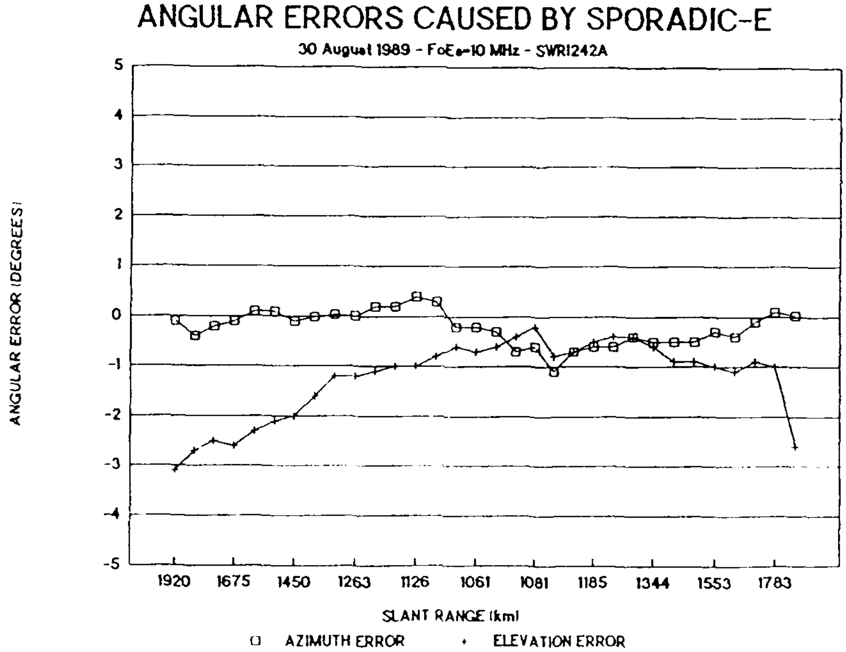


Figure 8 shows a measurement made on the afternoon of 30 August 1989. The pass was from south to north. The ionosonde indicated a critical frequency of 10 MHz, with intense blanketing of F-layer reflections. The Es cloud was almost devoid of horizontal gradients as virtually no azimuthal error is seen. Refractive bending in elevation, which decreases with range, is caused by the intensity of the ionization. The satellite reaches the edge of the Es cloud as it reaches the point of closest approach, and as it moves further north the errors become quite small.

Figure 8



It was hypothesized that the cumulative angular error from both the azimuthal and elevation components would increase as a function of E-region electron density. However, a review of cases with critical frequencies between 6 and 13 MHz indicated that the error level remained the same. Also, neither the azimuthal nor elevation components dominated changes in electron density. This is in part due to the thinness of the sporadic-E region.

SUMMARY

Ionospheric mapping using a low orbiting satellite with LoVHF beacons has provided a unique way to view both the benign and sporadic tendencies of the ionosphere.

The ionospheric E-layer does not normally contribute to signal refractive error, but the appearance of the sporadic-E layer contributes unpredictably. This study revealed nothing that would help in characterizing this unpredictability and assist in the modeling of this phenomenon. In all the cases reviewed for this experiment where sporadic-E occurred, the ionization ranged from small random clouds of increased ionization to relatively uniform layers. Errors in angle of arrival of the signal ranged from erratic and momentary to slowly varying and long lasting. Large areas were mapped on each satellite pass, which enabled analysts to see large clouds extending over 1200 km as well as small clouds of less than 100 km. The variations in refractive error could not be correlated to ionospheric electron density measurements made with a ground-based ionosonde. This study illustrates in greater detail just how unpredictable sporadic-E is. Each Es event is unique, and this makes accurate modeling impractical.

ACKNOWLEDGEMENTS

The author wished to acknowledge the assistance of Dr. David R. Lambert and Richard Sprague in the editing and review of this paper.

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